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Evidence of two unique variability classes from IGR J17091–3624

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ABSTRACT

IGR J17091–3624 is the second black hole X-ray binary after GRS 1915+105, which showed large and distinct variabilities. The study of these variability classes can be useful to understand the accretion-ejection mechanisms of accreting black holes, and hence to probe the strong gravity regime. We report the discovery of two new variability classes (C1 and C2) from IGR J17091–3624 from the 2011 outburst *Rossi X-ray Timing Explorer* data. These unique classes will be useful to have complete details about the source, and to learn new aspects about variabilities. For examples, the C1 class shows that the intensity and period of oscillations, energy spectrum and power spectrum can clearly evolve in tens of seconds. Moreover, in such a small time scale, soft-lag becomes hard-lag. the C2 class shows that the variability and the nonvariability can occur at similar energy spectrum, and a soft state is not required for variability to happen.

Key words: black hole physics — X-rays: binaries — X-rays: individual: (IGR J17091-3624, GRS 1915+105)

1 INTRODUCTION

In its 16 years of service, the *Rossi X-ray Timing Explorer* (*RXTE*) detected around ∼40 black hole X-ray binaries (BHXB; (Rodriguez et al. 2011; Remillard & McClintock 2006)), among which GRS 1915+105 is the most extraordinary and prolific in terms of its unique variabilities (Mirabel & Rodriguez 1994; Eikenberry et al. 1998; Yadav et al. 1999; Belloni et al. 2000). This source showed about 12 types of distinct classes, whereas no such distinct fast variabilities in the intensity were observed from any other BHXBs (Belloni et al. 2000; Yadav et al. 1999). Therefore, while a few limited X-ray states (e.g., low hard state, high soft state etc.) and transitions among them are studied for other BHXBs in order to understand the accretion-ejection mechanisms (Remillard & McClintock 2006; Homan et al. 2001; Belloni et al. 2000), GRS 1915+105 provides a unique laboratory to probe the inflow-outflow mechanism in many ways (yadav 2006). However, in order to use X-ray variabilities from GRS 1915+105 as a tool, one needs to understand them adequately. Although, it is possible that these variabilities originate from accretion disc instabilities, definite conclusions could not be made due to the lack of another source showing similar properties (Belloni et al. 2000).

Recent outburst of another black hole X-ray binary IGR J17091–3624 (e.g., (Krimm et al. 2011; Rodriguez et al. 2011)) has shown several X-ray variability classes (Altamirano et al. 2011b) similar to some of the classes (e.g., ν, ρ, α, β/λ, μ) observed from the GRS 1915+105 (Belloni et al. 2000). Observations of a given class with different intensities, energy spectra and power spectra from two different sources can be very useful to understand the physics of this class by constraining its models. For example, Pahari et al. (2011) studied the ρ-class properties of IGR J17091–3624 in detail, and compared them with those of GRS 1915+105. In this Letter, we report the discovery of two types of variabilities, which have never been observed from any black hole X-ray binary. Using spectral and timing studies, and from the evolution and repeatability of these variabilities, we establish their uniqueness, and define them as new classes (C1 and C2). The unique properties of C1 and C2 can be useful to understand the variabilities from IGR J17091–3624 and GRS 1915+105 in general, and hence to probe the accretion-ejection mechanisms.

2 DATA ANALYSIS

We analyze all the Good Xenon mode *RXTE* proportional counter array (PCA) data (203 obsIds; up to November 18, 2011) from the 2011 outburst of the transient black hole X-

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ray binary IGR J17091–3624. We examine light curves from all these obsIds, and find two new classes of variabilities (see § 3), which were never observed from any black hole X-ray binary, not even from GRS 1915+105. We call them the C1 class and the C2 class which are discussed in details in next section.

In order to check whether these are really new classes, as well as to understand their properties, we compute hardness-intensity diagram (HID; intensity versus hard colour), colour-colour diagram (CD; soft colour versus hard colour), power spectrum and time delay between two energy ranges. The hard colour is defined as the ratio of the background-subtracted count rate in $12-60$ keV to that in $2-5$ keV. The soft colour is the ratio of the background-subtracted count rate in $5-12$ keV to that in $2-5$ keV. The intensity is the background-subtracted count rate in $2-60$ keV. The colour value depend on the energy spectrum, and provide a convenient way to track the spectral evolution. Since proportional counter unit 1 (PCU1) and unit 2 (PCU2) were operating during observations of C1 and C2 classes, we use both of them. We compute a power density spectrum (PDS) from a 1024 s interval with a Nyquist frequency of 100 Hz in the entire PCA energy range, using the standard Fourier transform and considering the normalization of Miyamoto et al. (1991). The PDS is geometrically re-binned by a factor of 1.05, in order to suitably reduce the error throughout the frequency range. In order to find a plausible time delay between the variabilities in different energy bands, we calculate the cross correlation coefficient between light curves in two energy bands (see, for example, Sriram et al. (2010)). The shift of the peak of the cross correlation function from the origin provides the delay time. Since we are unaware of the time delay at the beginning, we started with 5 ms bintime. This choice ensures that the binsize is sufficiently smaller than the delay time. We cross-correlate the $2-5$ keV light curve with the $12-60$ keV light curve for different time bin sizes ranging from 5 ms to 20 s. For the bintime of 25 ms, we obtain a statistically significant distribution (i.e., high signal-to-noise ratio with small error-bars). We fit the peak (if any) with a Gaussian function to determine the peak position, and hence the time delay.

3 RESULTS

In this section, we discuss various properties (mentioned in § 2) of the C1 class and the C2 class observed from IGR J17091–3624. The light curve of the C1 class is somewhat similar to that of ρ class (Belloni et al. 2000; Pahari et al. 2011), but in this case, the ρ class-like variabilities are grouped in repetitive segments. There are other unique properties which make the C1 class different from the ρ class. For example, within one variability group of the C1 class, even in less than 200 s, the shape and frequency of the intensity oscillations and the hard colour values evolve substantially. For example, in Fig. 2, during the first 45 s (first segment) the lightcurve has moderate oscillation frequency and relatively low peak intensity, while the hard colour values are relatively high during intensity dips. During the next 80 s (second segment; Fig. 2), the oscillation frequency and intensity increase, while the hard colour values during intensity dips are relatively low. During the last 45 s (third segment; Fig. 2), the oscillation frequency decreases, the oscillation peak intensity remains relatively high, and the hard colour values during intensity dips remain relatively low. The spectral evolution in the relatively short time scale is also seen from the HIDs and CDs (Fig. 2), especially from the hard colour range and the soft colour range populated for each segment. These types of spectral and intensity evolutions in such a short time scale have never been observed for the ρ class. In the same short time scale, the power spectrum of C1 class also evolves, as indicated from the appearance (in first and third segments) and the disappearance (in second segment) of a plausible quasi-periodic oscillation (QPO) near 2 Hz with the significance of 2.9σ and 2.6σ respectively, as well as the change of shape and total integrated power of the power spectrum in $0.05-10.0$ Hz (Fig. 3). Contrary to this, the power spectrum (including QPOs) of ρ class remains stable for much longer time. Finally, we find that the $2-5$ keV photons lag behind the $12-60$ keV photons by 0.12 ± 0.04 s in the first 45 s of Fig. 2 with the statistical accuracy of 2.9σ. But in the last 45 s (third segment) of Fig. 2, the $12-60$ keV photons lag behind the $2-5$ keV photons by 0.58 ± 0.03 s with the statistical accuracy of 18.5σ(see Fig. 3). In case of ρ class, this time delay does not evolve. For the ρ variabilities from GRS 1915+105, we find that the $12-60$ keV photons lag behind the $2-5$ keV photons by a non-evolving value of 3.61 ± 0.06 s. These show that the C1 class is different from the ρ class, and is a unique class. Besides, the repeatability of the C1 variability (June 28, 29 and July 20, 23, 24, 2011) argues that it can be defined as a new class. Fig. 1 shows that the source evolved from the ρ class into the C1 class. After that, it evolved into a β-type class with hard, quiescent dips but without soft dips (see panel *C* of Fig. 1) (Altamirano et al. 2011b; Belloni et al. 2000).

The light curve of the C2 class alternately shows a nonvariable substate and a highly variable substate (Fig. 4). Light curves with such structures have never been seen from any black hole X-ray binary, not even from GRS 1915+105. The highly variable substate can last for $\sim 300-400$ s, and the transition between the two substates can happen as rapidly as in ~ 5 s. The average intensities of the two substates are similar to each other (Fig. 5). This figure shows that the transition from the nonvariable substate to the highly variable substate happened without clear change of hard colour values, which is unusual and hardly seen in other black hole X-ray binaries. The mean values of hard colour and soft colour are similar in both the substates (which is also unusual among black hole X-ray binaries), although these colours fluctuate more in the highly variable substate (see Fig. 5). Fig. 4 shows that IGR J17091–3624 evolved from a strong (roughly uniform) variability dominated state into the C2 class variability, and then it transitioned into a nonvariable state. This is unusual, because for GRS 1915+105, a highly variable state transitions into a nonvariable state usually via a state having long quiescent dips. The power spectra of the two subsets are different from each other (Fig. 6). The total integrated rms (in $0.05-10$ Hz) of the nonvariable state is at least 11 times lesser than that of the variable state, which is not very surprising. However, there is a broad hump-like feature around 0.2 Hz in the PDS of the nonvariable state. Based on the above unique properties of the C2 variability, as well as its repeatability (August

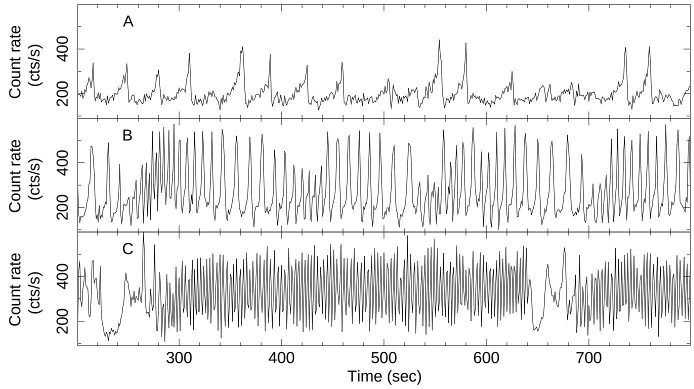

Figure 1. *RXTE* PCA light curves (2 − 60 keV; 1 s binning) of IGR J17091–3624. Panel *A*: June 25, 2011 data (ρ class); panel *B*: June 29, 2011 data (C1 class); and panel *C*: July 01, 2011 data (see § 2).

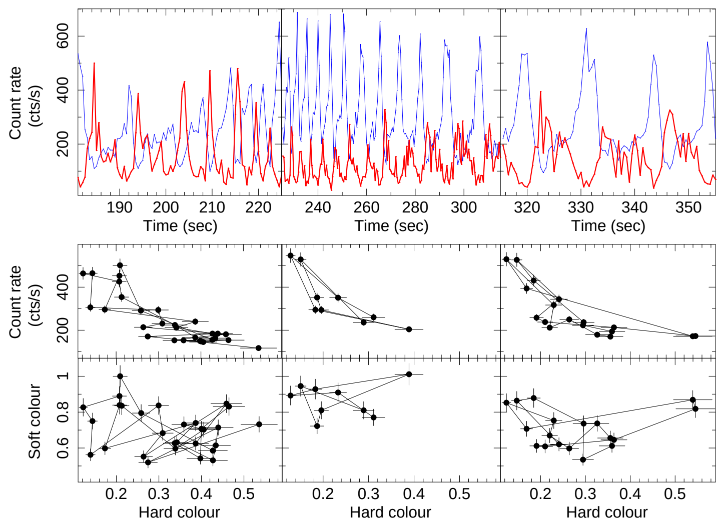

Figure 2. *RXTE* PCA light curves, CD and HID of the C1 class of IGR J17091–3624. *Top panels:* count rate (blue line) and hard colour (red line) with time. The hard colour values are multiplied with 500 to bring them in the scale of count rates. These adjacent panels show that the shape and frequency of the C1 class variability evolve significantly in tens of seconds. *Bottom panels:* HID and CD corresponding to each light curve segment of the top panels (see § 2 and 3).

25, 26 and September 21, 22, 23, 28, 2011), it can be defined as a new class.

4 DISCUSSION AND CONCLUSIONS

IGR J17091–3624 is the only black hole X-ray binary after GRS 1915+105, which showed a few types of large intensity variabilities. Some of these are similar to those seen from the GRS 1915+105. Why is the discovery of new variability classes important? As Belloni et al. (2000) pointed out, this gives the chance to look for the basic 'states' of the source, and to have complete details about the source. Besides, the classes have been modeled to probe the physics of accretion-ejection processes in case of the accreting black hole GRS 1915+105 (e.g., Neilsen et al. (2011)). Therefore, our finding of two new variability classes will be useful to obtain detailed understanding of IGR J17091–3624 and GRS 1915+105, as well as to probe the inflow-outflow mechanisms of accreting black holes.

The main purpose of this Letter is to report the discovery of two new variability classes C1 and C2. An attempt to probe their physical origins and to discuss their implications will be taken up in future detailed studies. Nevertheless, here we list, what could be learn from these new classes. (1) In case of GRS 1915+105, it is observed that most of the highly variable states are stabilized (i.e., become non-variable) via long, nonvariable and quiescent dips (like hard dips in β class, long quiescence in α class, etc.). However, C2 class is an exception to this, where strong variabilities transition into a nonvariable state with similar average intensities, and long quiescent dips, before and after strong variabilities are not observed. This finding will have impact on models, which attempt to explain class transitions. (2) For GRS 1915+105, average hard colour decreases when the source transitions from a nonvariability into a variability state (Yadav et al. 1999). Besides, the variability from this source is always found in soft state. Contrary to this, In case of C2 class of IGR J17091–3624, both variable and nonvariable substates have similar mean hard colour, and transition from one substate to another does not require clear hard colour change. These show that variability does not necessarily require a different spectral state (for example, soft thermal

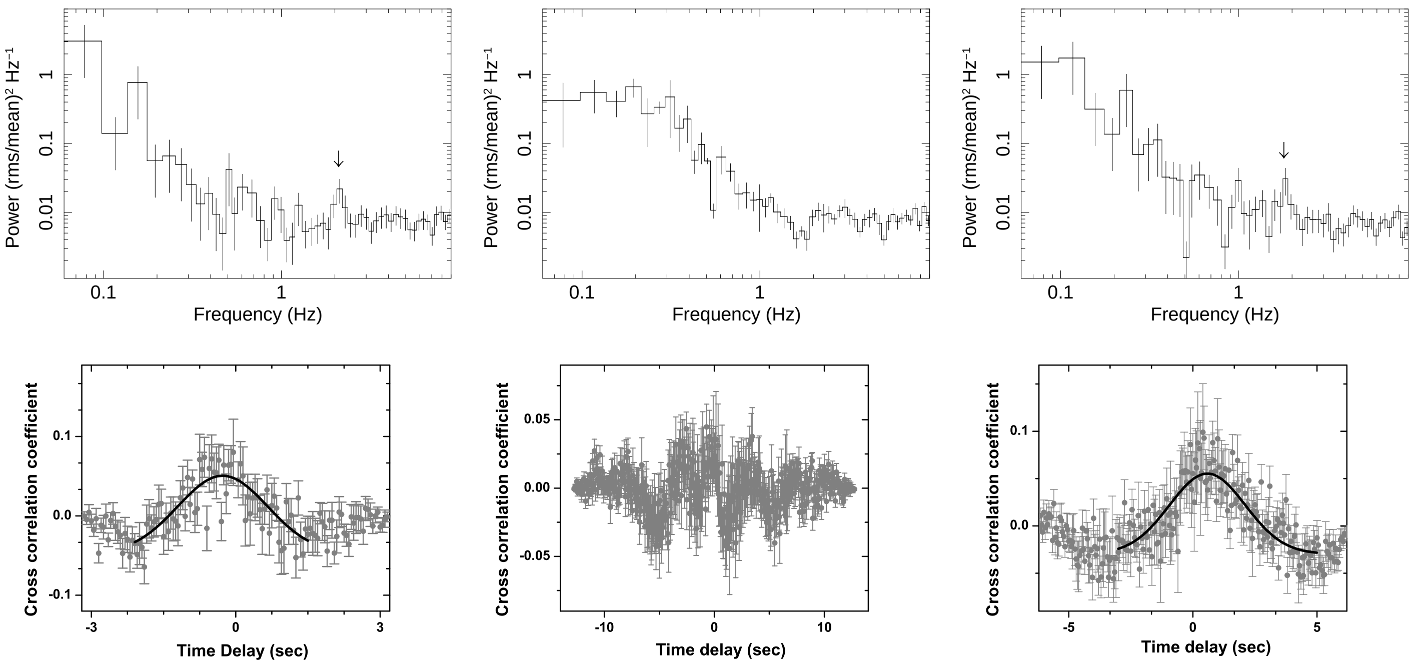

Figure 3. *Top panels: RXTE* PCA rms normalized power density spectrum corresponding to each of the adjacent time segments (as shown in the top panels of Fig. 2) for IGR J17091–3624. The error bars are of 1σ size, and the arrows indicate plausible QPOs. *Bottom panels:* time delay measurements between the $2-5$ keV light curve and the $12-60$ keV light curve using cross correlation techniques for each of the adjacent segments shown in top panels of Fig. 2. The peaks for the first and the third segments are fitted with a Gaussian function (see § 2 and 3).

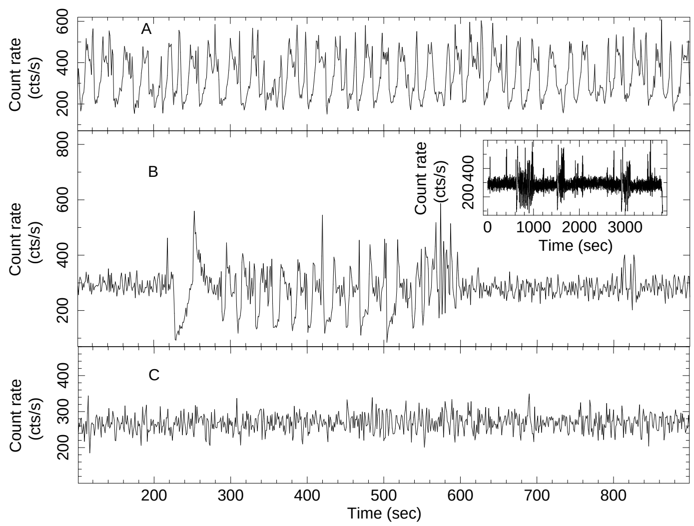

Figure 4. *RXTE* PCA light curves ($2-60$ keV; 1 s binning) of IGR J17091–3624. Panel *A*: September 20, 2011 data; panel *B*: September 28, 2011 data (C2 class); and panel *C*: September 29, 2011 data. The inset of panel *B* shows the same C2 class light curve for longer duration, so that several variable segments are seen (see § 2).

state) from the spectral states of nonvariability, and hence this will have impact on the variability models. (3) The finding of rapid evolution of spectral and timing properties during C1 class will also be useful to constrain the variability models (Mineo et al. 2012; Neilsen et al. 2011). Especially the change of soft lag into hard lag in tens of seconds could be useful to constrain the properties (e.g., location, size) of spectral components. Such a time delay reversal may indicate a strong coupling among the spectral components. (4) Finally, the disappearance and reappearance of a plausible ~ 2 Hz QPO in tens of seconds for C1 class may have impact on the models of accretion disc instabilities. Note that these instabilities are widely believed to be responsible for the variabilities of GRS 1915+105 (Belloni et al. 2000).

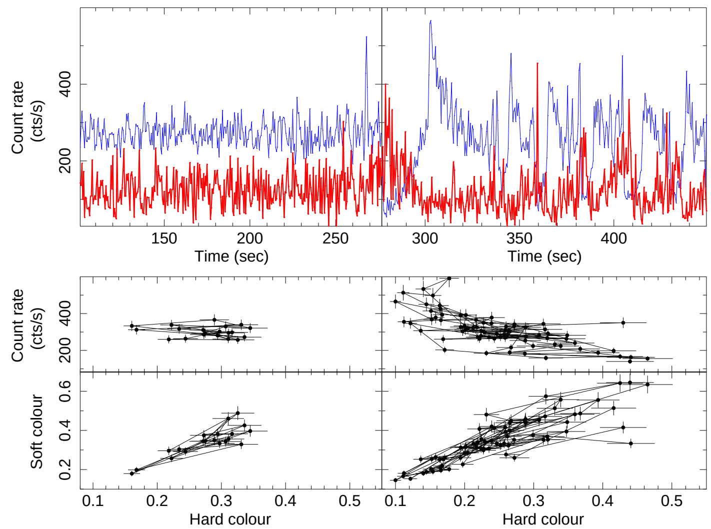

Figure 5. *RXTE* PCA light curves, CD and HID of the C2 class of IGR J17091–3624. *Top panels:* count rate (blue line) and hard colour (red line) with time. The hard colour values are multiplied with 500 to bring them in the scale of count rates. These adjacent panels show the natures of the non-variability and the variability portions of the C2 class. *Bottom panels:* HID and CD corresponding to each light curve segment of the top panels (see § 2 and 3).

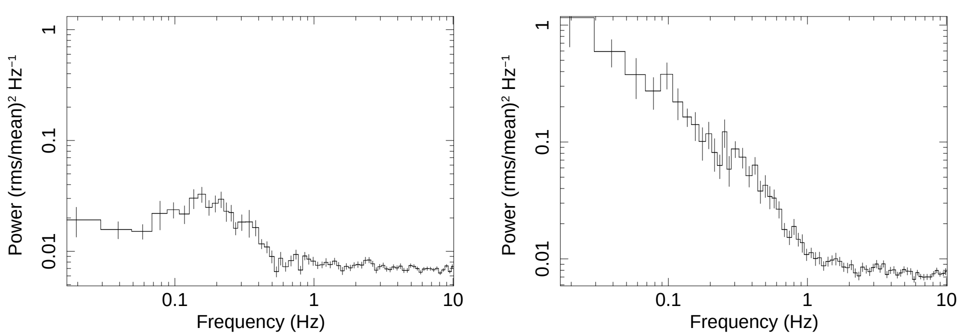

Figure 6. *RXTE* PCA rms normalized power density spectrum corresponding to each of the adjacent time segments (as shown in the top panels of Fig. 5) for IGR J17091–3624. The error bars are of 1σ size.

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